MEASUREMENTS OF ABSOLUTE, SINGLE CHARGE EXCHANGE CROSS SECTIONS OF H^+, He^+ AND He^{2+} WITH H_2O AND CO_2

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ABSTRACT

Absolute measurements have been made of single electron charge exchange cross sections of H^+, He^+ and He^{2+} in H_2O and CO_2 in the energy range 0.3 – 7.5 keV/amu. Collisions of this type occur in the interaction of solar wind ions with cometary gases and have been observed by the *Giotto* spacecraft using the Ion Mass Spectrometer/High Energy Range Spectrometer (IMS/ HERS) during a close encounter with comet Halley in 1986. Increases in the He^+ ion density, and in the He^{2+} to H^+ density ratio were reported by Shelley et al. (1987) and Fuselier et al. (1991), and were explained by charge exchange. However the lack of reliable cross sections for this process made interpretation of the data difficult. New cross sections are presented and discussed in relation to the *Giotto* observations.

highly charged ions

1. INTRODUCTION

Charge exchange is an important process in solar and stellar atmospheres, the interstellar medium, in planetary magnetospheres and ionospheres, and in comets. The product ion from the charge-exchange collision reaction is usually left in an excited state, so that one or more photons can be emitted as the ion stabilizes. If the ion is highly charged, this can give rise to X-ray emissions. Recent observations of X-ray emission from comets (Lisse et al. 1986; Dennerl et al. 1997) and the Jovian aurora (Metzger et al. 1983; Waite et al. 1994), have been modeled using charge exchange (Cravens 1997, Häberli et al. 1997; Wegmann et al. 1998; Cravens et al. 1995; Kharchenko et al. 1998). In the case of comets, it has been proposed that the fully- and partially-stripped solar wind ions such as C^{5+}, C^{6+}, O^{6+}, and O^{7+} charge exchanging with neutral species from the comet (CO_2, CO, H_2O, *etc.*) produce the observed X-rays.

The solar wind ions H^+ and He^{2+} will also capture electrons from the cometary gases. Measurements at comet Halley were made of the density of H^+, He^+ and He^{2+} ions using the Ion Mass Spectrometer/High Energy Range Spectrometer (IMS/ HERS) aboard the *Giotto* spacecraft. Observations were made as a function of distance from comet Halley (Fuselier et el. 1991; Shelley et al. 1987). These results showed an increase in the He^+ density as the comet-to-spacecraft distance narrowed, a strong indicator of the effects of single-electron charge exchange by He^{2+}. Similarly, changes in the He^{2+} to H^+ ratio were explained by differences in charge exchange cross sections for the two ions. The modeling assumed cross sections of 5×10^{-15} cm^2 and 0.3×10^{-15} cm^2 for H^+ and He^{2+}, respectively (Fuselier et al. 1991). With few accurate experimental cross sections available, even qualitative analysis of the data was difficult. As will be shown below, the cross sections for H^+ and He^{2+} are comparable to one another, and are about $(1\text{-}1.5) \times 10^{-15}$ cm^2 at ion energies in the range 0.3-7 keV/amu.

2. EXPERIMENTAL METHOD

A new experimental beam line was designed and tested to measure absolute cross sections for charge exchange of highly-charged ions with neutral targets in the energy range 1-10 *q*keV (*q* is the ion charge). The experimental apparatus will be described in detail in a forthcoming paper (Greenwood et al. 1999). The essential features will be discussed here, and results for absolute charge-exchange cross sections of H^+, He^+ and He^2 with cometary molecules CO_2 and H_2O will be presented.

A description and schematic of the JPL highly-charged ion facility may be found in Chutjian et al. (1998). By way of summary, ions are produced in an electron cyclotron resonance (ECR) ion source capable of producing intense beams of partially or fully stripped ions. Mass to charge selection of the ions is achieved by a double-focusing 90° bending magnet. In the present measurements the isotope ^3He was used as a source gas to ensure an uncontaminated beam of He^+ and He^{2+} at a mass/charge of 3.0 and 1.5, respectively; free of, for example, O^{4+} and H_2^+ at a mass/charge of 4 and 2, respectively. [Use of the isotope will have negligible effect on the cross section. Collision times here (10^{-15} s) are shorter than vibrational periods (10^{-14} s) in the intermediate "quasimolecule" so that molecular details of the interaction can be taken as frozen (Kumar and Saha 1999).] The ion beam is subsequently directed into the charge-exchange arm of the apparatus, as shown in Figure 1. The ions are collimated by three small apertures before entering a gas cell filled with H_2O or CO_2. The pressure inside the cell is determined by measuring the pressure in the gas feed line using a capacitance manometer. A large conductance between the cell and manometer ensures that there is a small pressure difference between the two.

The beam is eventually collected in a deep Faraday cup where the ion current is measured. By applying a positive voltage to the reflecting apertures in front of the Faraday cup, He^{2+} can be reflected while ions charge-exchanged to He^{+} are transmitted and collected by the Faraday cup. To ensure 100% collection of the scattered ions, measurements were made at the lowest energies (where angular differential cross sections are expected to be broadest) using exit cell apertures of two different diameters. One aperture had twice the angular acceptance of the other. Within the statistical uncertainty no change in cross section was observed. This was indication that all the scattered products were being collected. With this full angular acceptance, absolute charge-exchange cross sections for He^{2+} in CO_2 and H_2O were obtained.

For singly charged ions the first technique of retarding-potentials is not applicable as the products are neutrals and their currents cannot be measured. However, a second technique can be used. By measuring the attenuation of the singly-charged ion beam as a function of pressure the single charge-exchange cross section can be obtained. If the cross section for ionization or charge exchange of the neutrals formed from single charge exchange is small, a logarithmic plot of the transmitted current against pressure should be a straight line. This is confirmed by the attenuation plots shown Figure 2. The He^{+} beam produced by the ECR may have a significant proportion of 2^2S metastable ions. If there were metastable ions in the beam, the attenuation plot would show two different slopes, corresponding to charge exchange from the ground and metastable states. If the metastable state accidentally had the same charge exchange cross section, then there would only be a single slope. Hence either way the straight line in Figure 2 indicates that the present measurements are unaffected by metastable states.

A summary of the sources of error in the experiment is given in Table 1. The largest error in both the reflecting aperture and ion attenuation techniques is the stability of the incident ion beam. This error is larger for the attenuation method as a single plot takes about 5 minutes, compared to about one minute for the reflecting apertures method. To account for the variability of the ion beam current multiple measurements were made in both the reflecting apertures and attenuation methods. A mean of the results was obtained, and the random error estimated from the standard deviation. The total errors are determined from the quadrature sum of the individual errors.

3. RESULTS AND DISCUSSION

The present cross sections, along with previous results, are shown in Figures 3 and 4 for H_2O and CO_2, respectively. Only H^+ in H_2O (Figure 3) has been investigated extensively in prior work. However most of the results are nearly 30 years old and are in limited agreement. The recent H^+ data by Lindsay et al. (1997) have small error bars and are in excellent accord with our measurements. Results of Koopman (1968) for H^+ in H_2O are nearly an order of magnitude below all other results, whereas results for CO_2 (Figure 4) are in reasonable agreement with present measurements. A compilation of $H^+ + CO_2$ results by Barnett et al. (1977) is in good agreement with our work.

In the case of He^+, the only previous studies of He^+ in H_2O were by Koopman (1968), but are nearly an order of magnitude lower than present data. Since the $H^+ + H_2O$ data of Koopman were also low, these results are deemed unreliable. However, for He^+ in CO_2 (Figure 4) the limited results of Koopman (not shown) are in much better agreement with our work.

The only previous results for He^{2+} in H_2O and CO_2 in this energy range are limited to a few measurement by Rudd et al. (1985), for which agreement is good for CO_2 but poor for H_2O.

To model some of the observations made by IMS/HERS of the densities of H^+, He^+ and He^{2+} in comet Halley, Fuselier et al.(1991) made several assumptions about the charge-exchange cross sections of these ions in cometary gases. The cross sections were taken to be constant with collision energy, equal to 5×10^{-15} cm^2 and 0.3×10^{-15} cm^2 for H^+ and He^{2+} respectively. The cross section for He^+ in H_2O was taken to be smaller than that for He^{2+}(Shelley et al. 1987). It can clearly be seen (Figures 3 and 4) that over the range of solar wind velocities 200-800 km/s (or 0.2-3.2 keV/amu), most of these assumptions are unreliable. Our measurements for H^+ and He^{2+} indicate that the cross sections vary in the ranges (2.0-1.0 $\times10^{-15}$ cm^2) and (0.5-1.5 $\times10^{-15}$ cm^2), respectively. The cross sections of He^+ compared to He^{2+} are comparable to, or somewhat smaller for collisions in H_2O; and are comparable to, or somewhat larger in CO_2. The charge-exchange cross sections used by Fuselier et al. were based on values used previously by Ip & Heish (1982), who assumed the He^{2+} cross section to be 3 times greater than the cross section of He^{+}, measured by Koopman. However, as has been shown above, the results of Koopman for H^{+} and He^{+} collisions in H_2O are an order of magnitude smaller than both our data and previous results.

These findings indicate the measured ratio of the He^{2+} and H^{+} cross sections is considerably less than that used by Fuselier et al. to explain the increase in He^{2+} to H^{+} density ratio as comet Halley is approached. Since the IMS/HERS instrument was unable to separate the solar wind He^{2+} and H^{+} ions from cometary H_2^{+} and H^{+} ions, it is possible that contamination by the latter ions is the cause of the observed density ratio increase, especially in the so-called "mystery region". Such extra production of H_2^{+} and H^{+} could arise, for example, from solar-wind sputtering effects on the comet surface, or from additional surface recombination to produce H_2 or H_2^{+} at the comet.

The observations of an increase in the density of He^{+} at distances of 10^5 km, are unambiguous, The ion He^{+} is neither a cometary or solar wind ion and can only be produced from solar wind He^{2+} charge-exchanging. The model by Fuselier et al. using a cross section of 0.3×10^{-15} cm^2 significantly underestimates the observed density increase by a factor of 4. Our results indicate that the cross section is 2-4 times larger than this value, which is in agreement with the conclusions of Shelley et al.(1987).

5. CONCLUSION

Cross sections for single charge exchange of H^{+}, He^{+} and He^{2+} in CO_2 and H_2O have been measured and correlated with the observations of solar wind ions near comet Halley. The cross sections for H^{+} and He^{2+} in CO_2 and H_2O were found to be factors of up to 3-4 times different than those used by Fuselier et al. to model the Halley observations. Our results do not explain the increase in the He^{2+} to H^{+} as the comet is approached, particularly in the "mystery region." Contamination of the solar wind He^{2+} and H^{+} ions by H_2^{+} and H^{+} cometary ions may be the reason for this discrepancy. The observations of He^{+} density are less ambiguous, and consistent with our measured charge-exchange cross sections for He^{+} and He^{2+} in the cometary neutrals H_2O and CO_2.

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TABLE 1

SUMMARY OF EXPERIMENTAL ERRORS

Source of Error	**Random Error (%)**		**Systematic Error (%)**	
	Attenuation	Reflecting Aperture	Attenuation	Reflecting Aperture
ion beam stability	5-15	3-8	---	---
pressure measurement	<1	1-5	2	2
beam current measurement	---	---	<0.5	<0.5
gas temperature	<1	<1	1.0	1.0
cell collision length	---	---	1.5	1.5

TABLE 2

ABSOLUTE CHARGE EXCHANGE CROSS SECTIONS FOR H^+, He^+ AND He^{2+} IN H_2O

Energy (keV/amu)	H^+	total error	He^+	total error	He^{2+}	total error
0.3330			0.606	0.037		
0.6670			0.533	0.026	0.577	0.034
0.8330					0.737	0.025
1.0000			0.542	0.018	0.798	0.032
1.3300					1.012	0.068
1.5000	1.74	0.14				
1.6700			0.555	0.034	1.064	0.061
2.0000	1.62	0.10			1.179	0.071
2.6700					1.286	0.047
3.0000	1.48	0.10				
3.3300					1.396	0.074
4.0000					1.364	0.048
4.6700					1.368	0.047
5.0000	1.285	0.074				
5.3300					1.359	0.043
6.0000					1.378	0.053
6.6700					1.378	0.072
7.0000	1.160	0.086				

Notes: Units are 10^{-15} cm^2, and total errors are cited at the 1σ limit.

TABLE 3

ABSOLUTE CHARGE EXCHANGE CROSS SECTIONS FOR H^+, He^+ AND He^{2+} IN CO_2

Energy (keV/amu)	H^+	total error	He^+	total error	He^{2+}	total error
0.3330			1.149	0.031		
0.6670					0.407	0.013
0.8330			1.020	0.028	0.492	0.026
1.0000					0.567	0.023
1.3300					0.692	0.030
1.5000	1.538	0.059				
1.6700			0.959	0.026	0.872	0.040
2.0000					0.950	0.035
2.5000	1.434	0.055				
2.6700					1.100	0.057
3.3300					1.120	0.044
4.0000					1.156	0.056
4.6700					1.210	0.046
5.0000	1.270	0.077				
5.3300					1.222	0.079
6.0000					1.224	0.036
6.6700					1.202	0.035

Notes: Units are 10^{-15} cm^2, and total errors are cited at the 1σ limit.

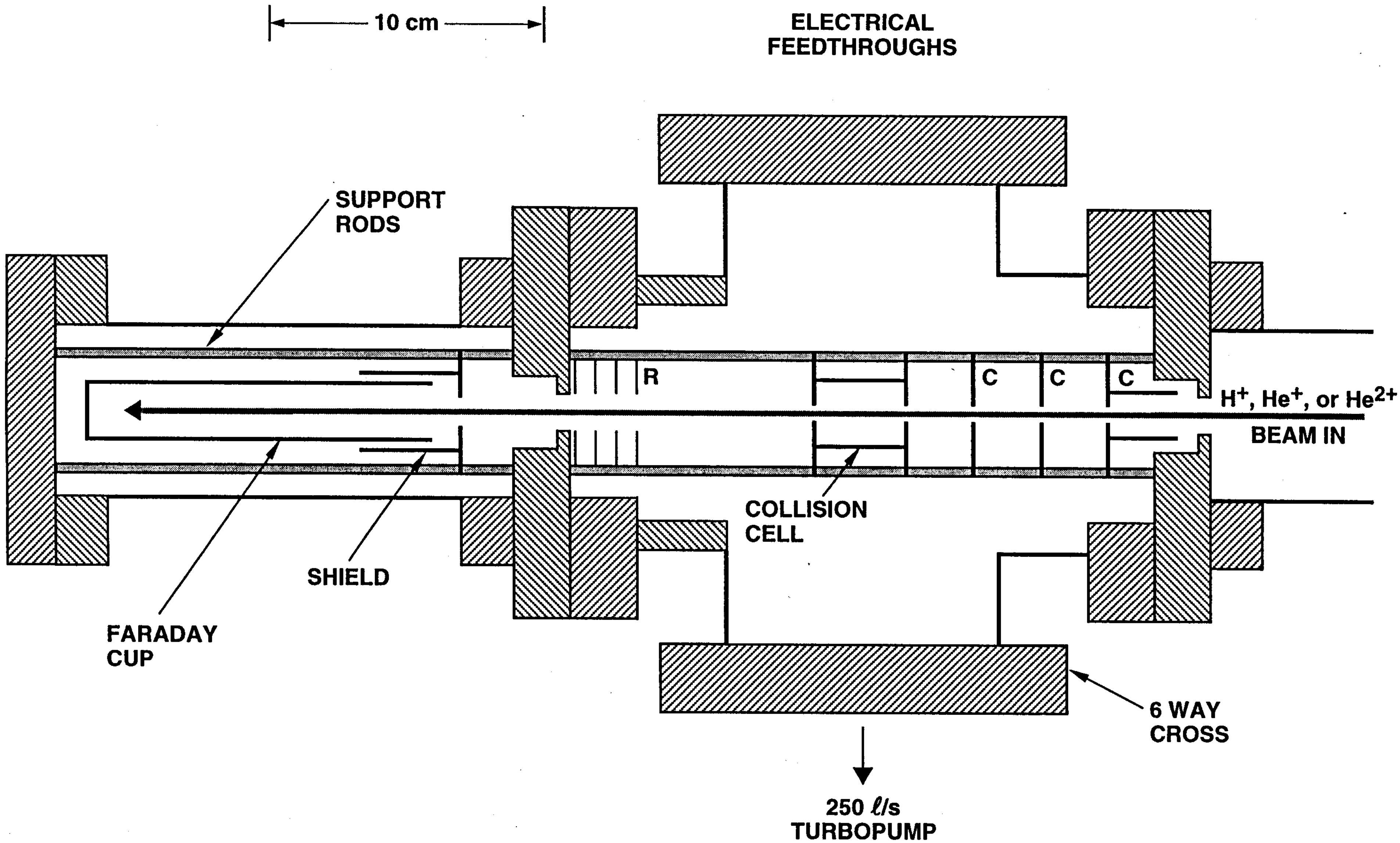
Figure Captions

Fig. 1. - The experimental charge exchange beam line. The ions H^+, $^3He^+$ or $^3He^{2+}$ from the electron-cyclotron resonance ion source enter from the right. The collision cell is filled with H_2O or CO_2, with the pressure monitored by a capacitance manometer (not shown). Collimating entrance apertures are indicated by **A** and reflecting apertures by **R**. The transmitted or attenuated beam currents are measured at the Faraday cup.

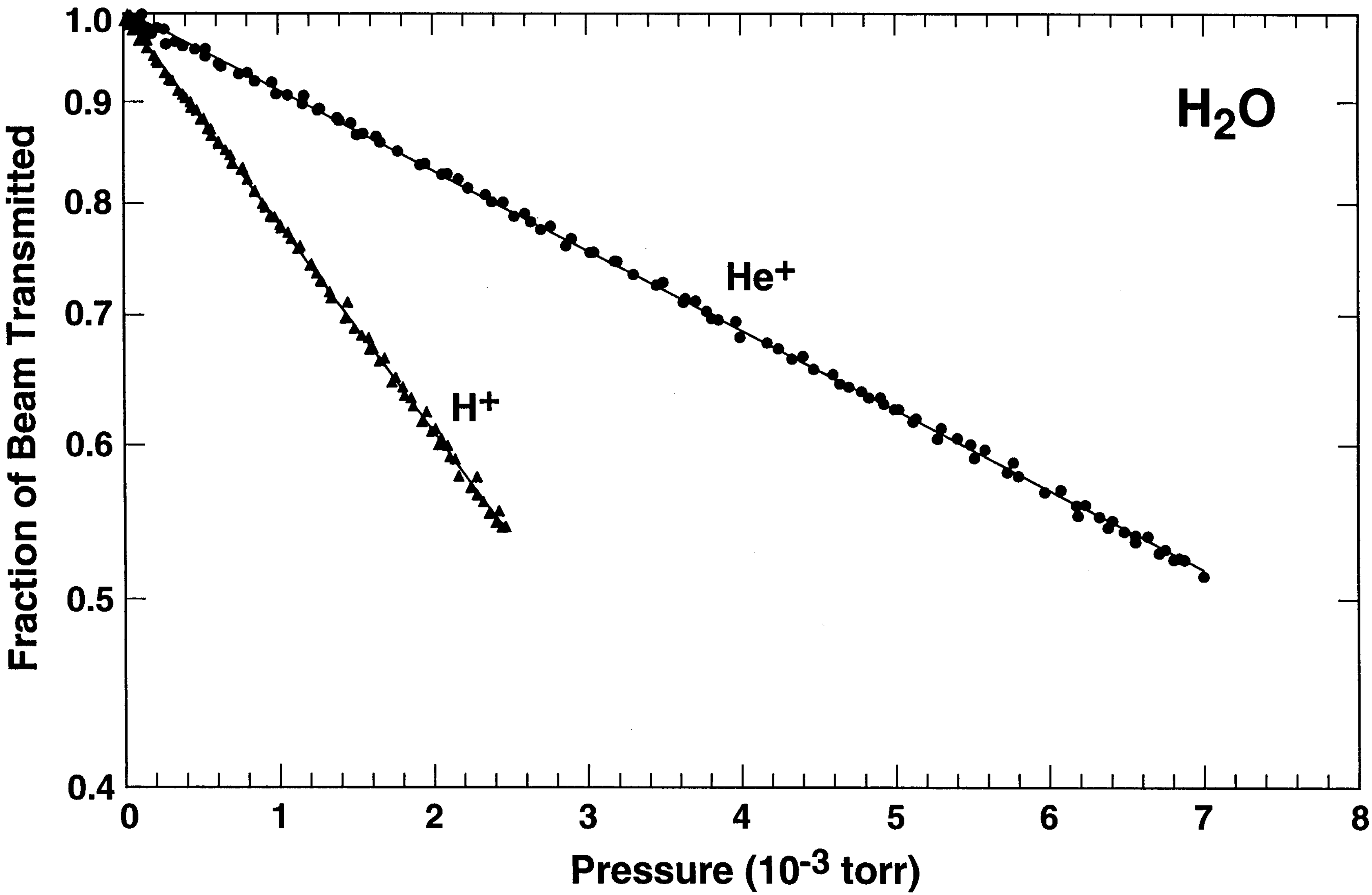
Fig. 2. - Attenuation plots in H_2O of H^+ at an energy of 3 keV/amu and $^3He^+$ at 1 keV/amu.

Fig. 3 - Absolute single charge exchange cross sections of H^+, He^+, and He^{2+} in H_2O. Present data are: H^+ (filled triangles), He^+ (filled squares), and He^{2+} (filled circles). Other data for comparison are for H^+ (open triangles, from Lindsay et al. 1997), H^+ (solid line) from Koopman (1968), and He^{2+} (open circles, from Rudd et al. 1985).

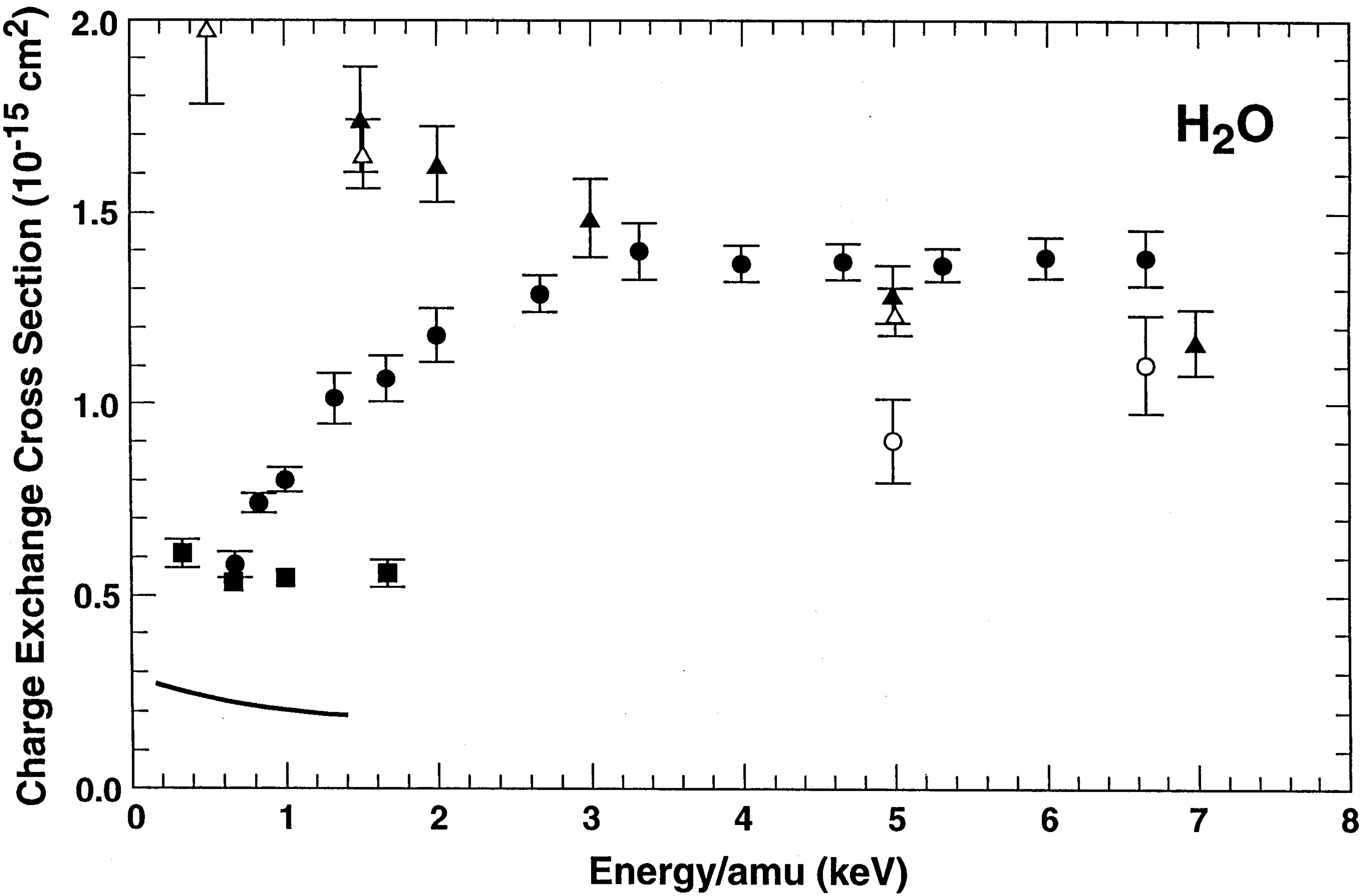
Fig. 4. - Absolute single charge exchange cross sections of H^+, He^+, and He^{2+} in CO_2. Legend is the same as for Figure 3, except for additional H^+ data from Barnett et al. (1977) (open triangles).



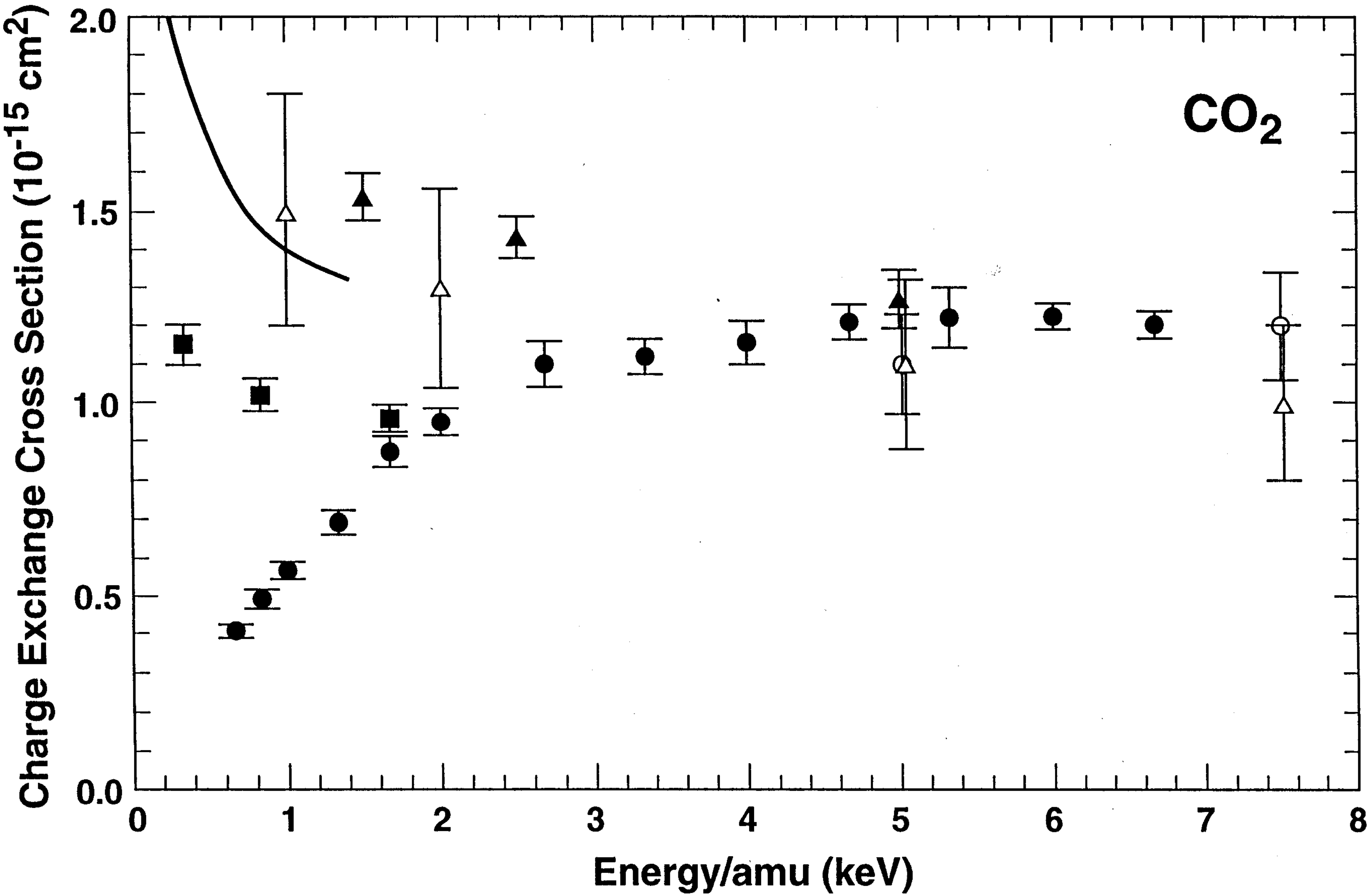
10 cm
ELECTRICAL FEEDTHROUGHS
SUPPORT RODS
R
C
C
C
H^+, He^+, or He^{2+}
BEAM IN
COLLISION CELL
SHIELD
FARADAY CUP
6 WAY CROSS
250 ℓ/s TURBOPUMP



H_2O
He+
H+
Fraction of Beam Transmitted
Pressure (10-3 torr)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0
1
2
3
4
5
6
7
8



H2O
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
7
8
Energy/amu (keV)
Charge Exchange Cross Section (10-15 cm2)



CO$_2$
Charge Exchange Cross Section (10^{-15} cm^2)
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
7
8
Energy/amu (keV)